Team DAD Technical Paper

DARPA Grand Challenge 2005

Submitted by:
David S. Hall (dhall@velodyne.com)
Bruce H. Hall (bhall@velodyne.com)
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Abstract

Team DAD's novel approach to GC 2005 is a 64 element rotating LADAR camera system employed as the single environment sensing system. The camera provides robust real-time 3-D terrain mapping under all conditions, including rain, darkness, and fog. The camera employs advanced techniques such as digital signal processing for multiple reflection discrimination, variable laser intensities, and redundant sub camera assemblies. The entire camera and navigation system is enabled by the use of 10 embedded TI C6416 DSP processors running assembly code.

Introduction

Team DAD is pleased to submit another entry into the DGC. Since DC I we have developed a revolutionary 64-laser LADAR terrain mapping system that we believe solves problems inherent in conventional terrain mapping and obstacle detection / avoidance systems. We believe that this LADAR system, combined with our existing autonomous route following technology, allows us to deploy a high-performance, high reliability autonomous vehicle. Our solution is extremely lightweight and can be retrofitted on virtually any vehicle due to the advantages of embedded DSP chips from TI. We look forward to demonstrating our solution at GC 2005.

David S. Hall once again leads team DAD. Mr. Hall designed and programmed all aspects of the Team DAD vehicle. He was assisted by Chris Kallai, Rick Yoder and Will Conway in the areas of mechanical engineering, Tri Luong in the area of Electrical Engineering, and Ed Stephens for drafting and documentation. Bruce Hall acts as team leader and key PR contact, and Ann Gargiulo assists in Marketing Communications. Our key sponsor is Texas Instruments.

1. Vehicle Description

1.1. Describe the vehicle. If it is based on a commercially available platform, provide the year, make, and model. If it uses a custom-built chassis or body, describe the major characteristics. If appropriate, please provide a rationale for the choice of this vehicle for the DGC.

> The Team (DAD) entrant vehicle is a standard 2003 Toyota Tundra (the same one we used in GC I). Specific data about this vehicle (size, weight, etc.) is available at http://www.toyota.com/html/tcuv/brochures/03_tundra.pdf. We are using the SR5 V8 Access Cab model.
>
> This vehicle was chosen for its reliability, space under the hood for retrofitting steering and brake motors, and electronic throttle features. The Team DAD navigation and obstacle detection systems could be retrofitted on virtually any vehicle.

1.2. Describe any unique vehicle drive-train or suspension modifications made for the DGC including fuel-cells or other unique power sources.

> The vehicle will be stock except for desert racing tires and a retrofitted extra fuel cell to provide a total fuel capacity of approximately 40 gallons.

2. Autonomous Operations

2.1. Processing

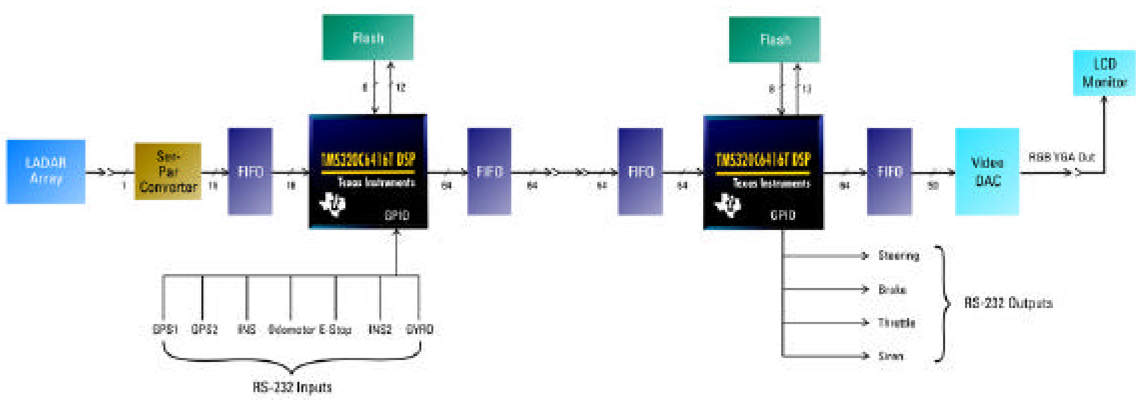
2.1.1. Describe the computing systems (hardware and software) including processor selection, complexity considerations, software implementation and anticipated reliability.

> The computer system uses TI's C6416 digital signal processors (DSPs) for computational power. They were chosen for their low power and high processing throughput. The software is entirely written in-house using assembly language – there are no operating systems, networks, or other housekeeping overhead. DSP chips have been in use for decades controlling mission-critical systems for commercial and government applications so the reliability should be excellent.

The computer system uses only a few watts of power, having no moving parts or fans.

The entire DAD navigational system is built from the ground up exclusively for this purpose. Thus, all computing power is embedded and occupies a dramatically smaller footprint than conventional computing systems.

2.1.2. Provide a functional block diagram of the processing architecture that describes how the sensing, navigation and actuation are coupled to the processing element(s) to enable autonomous operation. Show the network architecture and discuss the challenges faced in realization of the system.



See the above block diagram of the key functional aspects of the system and how they interconnect. Beginning at the left side of the diagram, the LADAR terrain mapping system is shown. This system employs 8 C6416 DSP chips and 64 lasers all rotating in a drum atop the vehicle providing a constantly updated highly accurate terrain map. A single channel high-speed connection feeds the mapping data to a serial-to-parallel converter, which then populates a FIFO memory array. The first of two C6416 DSPs then inputs the LADAR information from the FIFO array along with information from the two GPSs, two INSs, FOG Gyro, Odometer, and E-Stop. This DSP then performs all the analysis needed to decide the vehicle's path, which is then fed via two-FIFO arrays to the next C6416, which actually controls the vehicle (note the steering, brake, throttle, and siren outputs). The second C6416 DSP also controls the video display, which allows viewing of the LADAR image for debugging purposes.

Other than having to design and build the system from scratch, the realization of the system wasn't challenging. Lessons learned from GC I drove the requirements for the LADAR terrain mapping and obstacle detection system described in more detail below.

2.1.3. Describe unique methods employed in the development process, including model driven design or other methods used.

Team DAD designed and built all components in use for its DGC entry from the ground up dedicated for this purpose. Team DAD has dedicated onsite resources in the areas of CAD/CAM design, drafting, PC board layout, machine shop prototyping, electrical engineering, mechanical engineering, documentation, assembly, testing and debugging.

Team DAD is wholly owned by Velodyne Acoustics, designer and manufacturer of world-class home theater subwoofers. Team DAD operates out of Velodyne's 65,000 square foot headquarters facility in Morgan Hill, Ca.

The LADAR terrain mapping and obstacle detection system was fully conceived and modeled using the SolidWorks CAD/CAM system. PADS was used for all PC board layout. TI's Code Composer was used for all software development. All software code is written in-house in assembler language.

2.2. Localization

2.2.1. Explain the GPS system used and any inertial navigation systems employed during GPS outages (as in tunnels). Include a discussion of component errors and their effect on system performance.

Dual GPS receivers are used, both to establish direction at rest and to provide redundancy. The first is a Navcom 2050G using the Starfire subscription service and the second is a Novatel ProPak-LB receiver using the Omnistar subscription service. These subscription services typically deliver 2 inch accuracy under full sky-in-view conditions and when operating in dual-differential mode.

The inertial navigation system is based upon a FOG gyro (model KVH DSP-5000) and the vehicle odometer. The GPS receivers are used to correct the errors in the inertial system. Also, there is a 6-axis inertial system mounted on the LADAR head (described below) that is used to correct the LADAR signal as well as provide pitch and roll information for correcting the FOG gyro signal. The third gyro in the 6-axis system is used as a redundant backup for the FOG gyro. Additionally, there is a Honeywell TALON-4000 unit that might be installed by race time.

The FOG gyro and odometer system are adequate to navigate properly until GPS signals are reacquired while passing through a tunnel. However, the system defaults to the LADAR system anytime the GPS signal is not stable.

2.2.2. If map data was an integral part of the vehicles navigation system, describe the requirements for this data and the way in which it was used.

No maps are used in the system.

2.3. Sensing

2.3.1. Describe the location and mounting of the sensors mounted on the vehicle. Include a discussion of sensor range and field of view. Discuss any unique methods used to compensate for conditions such as vibration, light level, rain, or dust.

A unique LADAR terrain mapping and obstacle detection system is employed as the single sensor. The 64-element LADAR system has a 360-degree field of view and a 20-degree vertical range. It is mounted on top center of the cab, giving it a clear view in all directions, and rotates at a rate of 600 RPM. The camera is shock mounted, and has an INS sensor system mounted on it to report exact pitch and roll of the unit that is used by navigational computers to correct for these forces. The unit generates its own light and uses a proprietary filter to reject sunlight, so it works well under all lighting conditions. Since the whole camera spins, dust and rain are spun off the unit as it rotates. The LADAR unit is capable of seeing through fog and heavy rain by ignoring early reflections. The unit has a dynamic power feature that allows it to increase the intensity of the laser emitters if a clear terrain reflection is not obtained.

The LADAR system is shown in the following photograph:

2.3.2. Discuss the overall sensing architecture, including any fusion algorithms or other means employed to build models of the external environment.

The LADAR unit sends its data in the form of range and intensity information to the master computer. Using standard trigonometry the range data is converted into x and y coordinates and a height value. The height value is corrected for the vehicle's pitch and roll so the resulting map is with reference to the horizontal plane of the vehicle. The map is then "moved" in concert with the vehicle's forward or turning motion. Thus, the camera's input is cumulative and forms a very high-density profile map of the surrounding environment.

This terrain map is then used to calculate obstacle avoidance vectors if required and, as importantly, maximum allowable speed for the terrain ahead. The LADAR system allows for identification of size and distance of objects in view, including the vertical position and contour of the road surface itself. Objects are not classified into categories per se – all objects are presumed solid and, if not road surface, to be avoided. The anticipated offset of the vehicle from a straight, level path, either vertical or horizontal, at different distances is translated into the G-force that the vehicle will be subject to when following the proposed path at the current speed. That information is used to determine the maximum speed that the vehicle should be traveling, and acceleration or braking commands are issued accordingly. In all cases the software seeks the best available road surface (and thus the best possible speed) still within the boundaries of the GPS waypoint being traversed.

2.3.3. Describe the internal sensing system and architecture used to sense the vehicle state.

Only INS data and the odometer are used to sense the vehicle state, as described above.

2.3.4. Describe the sensing-to-actuation system used for waypoint following, path finding, obstacle detection, and collision avoidance. Include a discussion of vehicle models in terms of braking, turning, and control of the accelerator.

See the block diagram referenced in section 2.1.2. A C6000 DSP chip takes in data from the LADAR system, from the GPS units, and from the INS inputs. It analyzes the desired vehicle path and speed as dictated by the RDDF and reconciles the possibility of navigating that path with the LADAR terrain map. If an acceptable route and speed is not found, the system looks off-centerline for an acceptable path. The method for determining best path and speed is similar to the analysis done in GC I. This chip has outputs for steering, brake, and acceleration controls.

All paths are assessed with respect to G-forces that would come to bear on the vehicle if that particular path were followed.

2.4. Vehicle Control

2.4.1. Describe the methods employed for common autonomous operation contingencies such as missed-waypoint, vehicle-stuck, vehicle-outside-lateral-boundary-offset, or obstacle-detected-in-path.

Missed waypoint: The DSP automatically reconciles current location with the active RDDF and determines nearest/next waypoint.

Vehicle Stuck. We have first-hand knowledge of this problem and have coded contingency plans for speed deviations from the desired (e.g. if lodged against a rock apply more throttle!).

Vehicle-outside-lateral-boundary-offset. The GPS centerline is always the preferred path of travel. If it must be deviated from, it is only done so to avoid obstacles and no more. After the obstacle has been negotiated, the system servos back to the GPS centerline. Vehicle boundary violations should never be encountered with this approach.

Obstacle-detected-in-path. The system automatically looks for alternate paths to avoid an obstacle. Once the obstacle has been negotiated it resumes normal navigation along the GPS centerline.

2.4.2. Describe the methods used for maneuvers such as braking, starting on a hill, or making a sharp turn without leaving the route boundaries.

Braking is used in the event of vehicle stop, change in speed limit, rough road surface that must be traversed, or if an unavoidable obstacle is detected.

Hills and other startup conditions are handled by the software that detects a low-velocity condition and applies more throttle.

Sharp turns. The steering servo motor can rotate the steering wheel 2 ½ turns in less than 1 second, and has more than enough lateral movement to accommodate the sharpest turn (e.g. switchbacks).

2.4.3. Describe the method for integration of navigation information and sensing information.

This is all integrated at a C6000 DSP chip as described in section 2.3.4.

2.4.4. Discuss the control of the vehicle when it is not in autonomous mode.

The vehicle is driven as a regular car when not in autonomous mode. Autonomous mode is engaged with three switches mounted on the roof of the vehicle just above the rear view mirror – one each for gas, brake and steering. When these switches are disengaged, the vehicle drives just like a regular truck. The light-footprint approach afforded by embedded DSP computers allows for a full compliment of passengers and cargo whether or not the vehicle is operating in autonomous mode.

2.5. System Tests

2.5.1. Describe the testing strategy to ensure vehicle readiness for DGC, including a discussion of component reliability, and any efforts made to simulate the DGC environment.

All computer processing and vehicle navigation is based on highly reliable DSP chips with proven field reliability in thousands of products worldwide. We have applied what we learned in the first race to harden our vehicle in the areas of tires, wiring, mounting hardware, and field-testing.

All Team DAD testing is done while passengers are inside the vehicle (this process was demonstrated at the site visit). We have already essentially perfected GPS waypoint following and are currently testing the LADAR system. These tests involve many trips around the block near our Morgan Hill facilities as well as field-testing over rough terrain in a nearby field. We had planned on rerunning the original GC I course but since the area has been closed we are seeking alternative desert-condition test sites.

2.5.2. Discuss test results and key challenges discovered.

The LADAR system has provided a robust terrain map under all conditions and has met our expectations regarding required data for terrain mapping and obstacle avoidance. As of this writing we are planning a long endurance test over desert conditions and expect to be fully ready for the DGC.